NETWORK PAVEMENT EVALUATION USING FALLING WEIGHT DEFLECTOMETER AND GROUND PENETRATING RADAR

By

A. Samy Noureldin, Ph.D., PE
Transportation Research Section Manager
INDOT, Division of Research
1205 Montgomery Street
P.O. Box 2279
West Lafayette , Indiana 47906
Tel. 765-463-1521
Fax.765-497-1665
snoureldin@indot.state.in.us

Karen Zhu, Ph.D.
Senior System Analyst
INDOT, Division of Research
1205 Montgomery Street
P.O. Box 2279
West Lafayette , Indiana 47906
Tel. 765-463-1521
Fax. 765-497-1665
kzhu@indot.state.in.us

Shuo Li, Ph.D., PE
Transportation Research Engineer
INDOT, Division of Research
1205 Montgomery Street
West Lafayette , Indiana 47906
sli@indot.state.in.us

Dwayne Harris, M.Sc.
Research Engineer
INDOT, Division of Research
1205 Montgomery Street
West Lafayette , Indiana 47906
harrisdwayne@hotmail.com

Prepared for Presentation at the 2003 TRB Annual Meeting and Publication as a Part of TRR Series

January 2003

ABSTRACT

Nondestructive testing has become an integral part for evaluation and rehabilitation strategies of pavements in recent years. Pavement evaluation employing the Falling Weight Deflectometer (FWD) and the Ground Penetrating Radar (GPR) can provide valuable information about pavement performance characteristics and be a very useful tool for project prioritization purposes and estimation of construction budget at the network level.

FWD deflection testing is an accurate tool for determining pavement structural capacity and estimating the required thickness of overlays and hence is an accurate tool for planning for or estimating required current and future construction budgets. GPR is the only tool that a highway agency may use to develop an inventory of pavement layers thicknesses in the most efficient manner possible. By estimating pavement layer thicknesses and stiffness properties more reliable projections of network rehabilitation strategies and needs can be established, thus resulting in cost effective use of available funds.

Traditional obstacles for the use of FWD and GPR in pavement evaluation at the network level used to be expenses involved in data collection, limited resources and lack of simplified analysis procedures.

This paper presents Indiana experience in pavement evaluation with the FWD and the GPR at the network level. A network level FWD and GPR testing program was implemented as a part of a study to overcome those traditional obstacles. This testing program included Interstate Highways I – 64, I – 65, I – 69, I – 70 and I – 74 and a number of U.S. Roads and State Routes.

It is concluded that network level testing employing the FWD and the GPR is a worthwhile, technically sound program that will provide a baseline of structural capacities of in – service pavements in Indiana. Periodical generation of necessary data will be useful for determining how best to quantify structural capacity and estimate annual construction budget.

FWD data on 2200 lane miles of the INDOT network is recommended annually for network level pavement evaluation. Only three FWD tests per mile are recommended. This amount of testing can easily be conducted in a testing season. The information collected will allow the equivalent of 100% coverage of the whole network in 5 years. GPR data is recommended to be collected once every 5 years (if another thickness inventory is needed), after the successful network thickness inventory conducted in this study. GPR data collection is also recommended at the project level and for special projects.

Both FWD and GPR data is recommended to be used as part of the pavement management system (together with automated collected data of international roughness index, IRI, pavement condition rating, PCR, rut depth, pavement quality index, PQI, and skid resistance).

Key Words: pavement layer thickness, FWD, GPR, deflection, backcalculation of layer moduli, effective structural number, remaining life, reliability, factor of safety.

INTRODUCTION

The Indiana Department of Transportation, INDOT, manages approximately 11,000 miles highway system of Interstates, U.S. Roads and State Routes employing a reliable management system. This system employs automated collected pavement surface condition data which includes pavement condition rating, PCR, international roughness index, IRI, rut depth, pavement quality index, PQI, pavement surface micro and macro – texture and skid resistance. INDOT (as well as most State Highway Agencies) does not employ pavement deflection data as a mechanistic tool for network level evaluation. Information regarding pavement layers thickness and stiffness by location is often not readily available and hence undue coring and destructive testing are often employed. This practice needs to be gradually improved especially with the national movement toward employing mechanistic based designs for new as well as rehabilitated pavements associated with issuing the "2002 AASHTO Pavement Design Guide". Information about existing pavement thickness, pavement layers structural stiffness (or adequacy), pavement deflection and resiliency of pavement support by location along highway pavement segments within INDOT jurisdiction needs to be obtained. Nondestructive testing of pavements appears to be the most practical approach to address this need.

In 1996, AASHTO committed to making its new pavement design guide (to be released in 2002), a mechanistic – empirical design procedure. The success of this new procedure will depend on the proper preparation of State DOT's such that the required pieces of information to implement mechanistic – empirical design are either already available or in the process of being collected. These pieces of information include collecting data related to pavement layers thickness and stiffness, surface deflection and subgrade resilience of pavements.

FWD is the most widely used device for collecting pavement surface deflection data and providing information related to mechanistic pavement design and material properties. Layers stiffness and subgrade resilience can be backcalculated employing FWD deflection basin information (1 – 6). Deflection testing of existing pavements employing the FWD was recently standardized by AASHTO and ASTM (AASHTO T 256, ASTM D 4694 and ASTM D 5858). In the last 15 years the FWD has become an essential tool for the evaluation of the structural capacity and integrity of existing, rehabilitated and newly constructed pavements (4 – 8).

GPR pavement related technology was developed during the SHRP program (9). GPR operates by transmitting short pulses of electromagnetic energy into the pavement. These pulses are reflected back to the radar antenna with the amplitude and arrival time that is related to the thickness and material properties of the pavement layers (10, 11). GPR provides a safe, nondestructive method for estimating pavement layers thicknesses. When GPR is mounted on a van, layer thickness profiles can be generated from radar survey data at highway speed. Thickness information are often very essential for pavement design engineers in order to determine how deep they can mill the pavement surface before resurfacing when rehabilitating a pavement. GPR technology is also extremely useful for pavement management, providing highway agencies to quickly collect inventory data on all pavements under their jurisdiction. GPR data collection is nondestructive and hence the need for frequent full depth pavement coring can be substantially reduced (10, 11). Core sampling is more time intensive and provides less data than GPR. Consider that the typical coring frequency for rehabilitation projects is three cores per lane mile. GPR analysis computes pavement thicknesses at 3 feet intervals and it does so without disrupting traffic. GPR data collection thus provides a more complete picture of the pavement thickness of a given stretch of highway in the time that it takes to drive across it. Coring becomes prohibitively impractical to use for network level inventories of pavement layer thicknesses. Thickness determination of existing pavement layers employing the GPR was recently standardized as an ASTM D – 4748.

Objectives:

The main objectives of the research study presented herein were:

1. To investigate the usage of the FWD and the GPR in pavement evaluation at the network level and to provide recommendations necessary for their future use in this context.
2. To develop an updated inventory of pavement layers thicknesses, pavement surface deflection, and pavement layers mechanistic characteristics that can be retrieved knowing roadway name, bound direction and reference post.
3. To use inventory data to investigate variability in pavement structural parameters, and estimate remaining life, required overlay thickness and necessary information for structural reliability analysis and safety factors computations for Indiana highway pavements.
4. To prepare necessary information for the first steps in implementing AASHTO 2002 Pavement Design Guide.

BACKGROUND

Ground Penetrating Radar, GPR

GPR is a high resolution geophysical technique that utilizes electromagnetic radar waves to scan shallow subsurface, provide information on pavement layer thickness or locate targets (12 – 15). Frequency of GPR antenna affects depth of penetration (12 – 15). Lower frequency antennas penetrate further, but higher frequency antennas yield higher resolution. To successfully provide pavement thickness information or scan an interface, the following conditions have to be present (12 – 15);

- The physical properties of the pavement layers must allow for penetration of the radar wave.
- The interface between pavement layers must reflect the radar wave with sufficient energy to be recorded.
- The difference in physical properties between layers separated by interfaces must be significant.

Physical (electrical) properties of pavement layers, thickness of pavement layers, and magnitude of difference between electrical properties of successive pavement layers impact the ability to detect thickness information using GPR (12 – 15). Depth of penetration of radar wave into a pavement layer depends on electrical properties of that layer. Radar wave will penetrate much deeper in an electric resistive layer than in an electric conductive layer. Layers with similar physical properties will be detected as one layer (12 – 15).

Conductive losses occur when electromagnetic energy is transformed into thermal energy to provide for transport of charge carriers through a specific medium. Presence of moisture or clay content in a pavement layer will cause significant conductive losses and hence will increase the dielectric permittivity and decrease depth of penetration (12 – 15).

GPR measurement of pavement layer thickness is calculated from the travel time of the radar wave;

$$\textbf{\textit{Pavement Layer Thickness, inches}} = \frac{5.9\Delta t}{\sqrt{\varepsilon_r}}$$

Δt = two- way travel time in nanoseconds (the time the radar wave travels to the target interface and back).

ε_r = relative dielectric constant of pavement layer.

Travel time is determined by interpretation of GPR scan (Figures 1 – 3). The Y-axis of a GPR scan is the two way travel time (in nanoseconds).

The relative dielectric constant of a pavement layer, ε_r, can be calculated knowing the amplitude of a radar wave reflected off the surface of that pavement layer and the amplitude of a radar wave reflected off a metal plate (12 – 15). This is usually done during calibration process conducted daily before data collection. The relative dielectric constant of a pavement layer can also be backcalculated knowing the real pavement layer thickness through coring.

Table 1 presents relative dielectric constants for some materials. Dielectric constants for INDOT pavements were found to be in the vicinity of 4.0 for asphalt surfaces and 7.1 for concrete surfaces. Presence of water in a pavement layer increases relative dielectric constant of that layer and hence testing with the GPR on wet pavement is usually avoided.

There is a minimum detectable layer thickness that is dependent upon radar antenna frequency. Higher frequency antennas offer higher resolution, but depth of penetration and power available decrease. Lower frequency antennas allow deeper penetration and more power, but resolution decreases. Minimum detectable layer thickness is related to resolution. Values for minimum detectable pavement layer thickness are given in Table 2.

GPR data can be collected such that a trace can be recorded every 3 ft or less depending on traveling speed. The X-axis of a GPR scan represents both the time and distance along the travel path (Figures 1 – 3). The Y-axis of the GPR scan is the two-way travel time. GPR scan should not be interpreted as a pavement cross section. The bands at the top of a radar scan (which represent the information above peak amplitudes) are disregarded. These bands are due to antenna design and do not represent interfaces. The peak amplitude represents the reflection of the air pavement surface interface. Bands that are associated with identifiable amplitudes and changes with location (traveling distance) are considered an interface and used for thickness calculations. Bands are sometimes caused by antenna ringing down. These bands do not represent reflections and hence are also disregarded. Please note that Figures 1 – 3 do not show associated amplitudes.

GPR testing does not require traffic control measures during data collection. Data collection can be done at 55 mph travel speed.

Falling Weigh Deflectometer, FWD

FWD Assembly

FWD is a device that applies an impact Force (load) on a circular plate to pavement surface. Force magnitude is the multiplication of a falling mass by impact acceleration. Sensors located at loading center and at fixed radii from loading center measure resulting surface deflections. Resulting set of deflections is known as the deflection basin. Deflection testing for INDOT is conducted using a fleet of 4 FWDs that are calibrated periodically using a local accredited calibration center based on SHRP and AASHTO standards (based on SHRP protocols).

Main FWD Fundamentals for Pavement Characterization

FWD center deflection data reflects the overall structural capacity of the pavement. This data has to be normalized to a standard load (generally 9000 pounds for highways) and a standard temperature (generally 68 F). Normalized center deflection data can be directly used for pavement evaluation and overlay design. Table 3 presents pavement structural condition as defined by center deflection and used by INDOT for general pavement structural evaluation.

Backcalculation of pavement layer moduli using FWD deflection basin measurements is commonly performed through a number of techniques that are currently available (3). ELMOD, MODULUS and MODCOMP are among those well known techniques that are typically used by pavement researchers and practitioners. In these techniques, pavement remaining lives in both fatigue and permanent deformation are computed and used for pavement evaluation and design purposes (3). The only disadvantage of these techniques is that they require layer thickness information through coring or GPR information. It becomes almost impossible to use these techniques for pavement structural characterization at the network level.

A simplified method for backcalculating pavement layer moduli and thicknesses directly from FWD deflection basin data was developed by Noureldin (5). In this method (BACKAL); layer moduli are estimated using FWD sensors that deflect exactly the same as the interfaces between pavement layers. Sensors used for moduli backcalculation are also used for backcalculating layer thicknesses (5). Pavement layer moduli and thicknesses estimated using this method were validated in a number of other research studies (6 – 8). The main advantage of this technique is that thickness data is not required for the backcalculation process and hence it provides a useful tool in analyzing FWD deflection data particularly at the network level.

FWD Testing Traffic Control Measures

On multi – lane highways a dump truck (called a buffer truck) loaded with sand and preferably equipped with an attenuator or arrow board follows the FWD in the testing lane approximately 100 to 200 feet behind. The sole purpose of this truck is to absorb the impact of any vehicle that disregards the previous two dump trucks. A second dump truck loaded with sand and equipped with an arrow board follows the testing crew in the testing lane approximately 500 to 1,000 feet from the FWD. A third dump truck loaded with sand and equipped with an arrow board (or transition sign if the arrow board is unavailable) is also used. This truck follows the FWD on the shoulder approximately 3,000 feet behind. On low volume multi-lane highways only two dump trucks may be used with one on the shoulder and the one following the FWD approximately 100-200 feet behind.

On a two lane highways a one lane obstructed – continuous moving set up is employed. Roadwork signs are erected along the shoulder within a mile of the work site. Several signs may be placed over an extended area so the work crews may travel greater distances while remaining inside the required one-mile posting. One traffic control vehicle will follow the FWD with flag persons at appropriate locations behind and in front of the moving operation. The terrain, traffic volume and weather conditions will determine the number and location of flag persons. A minimum of three persons may be required.

TESTING PROGRAM

Roadway Selection

Indiana interstate highways I – 64, I – 65, I – 69, I – 70 and I – 74 were selected to provide as much comprehensive coverage for the Interstate network system as possible (Figure 4). State Roadways; US – 6, US – 20, US – 24, US – 30 and US – 41 and State Routes SR – 1, SR – 3, SR – 5, SR – 19, SR – 32, SR – 37, SR – 49, SR – 67, and SR – 250 were selected such that districts, facility types and pavement types, are represented (Figure 4).

Data Collection

Data Collection Employing FWD

FWD was used to test the truck lane for both directions of traffic (east – west or north – south) of each selected roadway. Deflections were measured at 5 locations per mile, (every 1000 ft).It was believed that 5 locations is the minimum testing frequency to statistically represent a mile. Measurements were taken at approximately 3 ft from pavement edge. FWD measurements were obtained during the construction seasons of 2001 and 2002. Deflection testing was not conducted within cities or on locations where traffic may be disrupted or hazard to testing operator or road user was expected. Based on this scope, 12000 FWD measurements were taken.

Data Collection Employing GPR

GPR was used to test the truck lane for both directions of traffic (east – west or north – south) of each selected roadway at highway speed. Although GPR can continuously display thickness of pavement layers, it was decided to collect thickness data at only 5 locations per mile, (every 1000 ft) in order to be consistent with data collected by FWD. GPR data was obtained during the construction season of 2001.

Coring Data

A limited number of pavement cores were obtained for thickness measurements as a verification sample and to compare thicknesses obtained through coring with those obtained employing FWD and GPR. A core per mile was extracted from some selected roadways.

Response Variables

The following pavement characteristics were selected as response variables:

1. **FWD center deflection** normalized to a load of 9000 pounds and a temperature of 68 F. Table 4 presents temperature correction values used by INDOT in accordance to the 1993 AASHTO Pavement Design Guide (16). Correction factors are based on mean pavement temperature calculated using air and surface temperature data collected by FWD.

2. **Pavement layers (subgrade, support and surface) moduli** backcalculated from FWD data using the simplified method developed by Noureldin (5). All computations using this method were made with a spreadsheet without thickness information. Results obtained using this method match with those obtained through using the 1993 AASHTO Pavement Design Guide (16). The backcalculation process is conducted for FWD data before any temperature correction. Backcalculated HMA surface modulus values were normalized to 68 ^{0}F temperature using the following equations;

Temperature Corrected Surface Modulus = Surface Modulus / Correction Factor

$$\text{Correction Factor} = (1.0000008)^{314432-T^{3}}$$

T = mean pavement temperature, ^{0}F, calculated using air and surface temperature data collected by the FWD.

3. **FWD estimated surface and total pavement thickness** employing FWD data and the simplified backcalculation procedure developed by Noureldin (5).

4. **GPR estimated thicknesses** of pavement layers.

5. **Surface and support layer coefficients** calculated employing moduli values and the formula reported by Noureldin (5) and the 1993 AASHTO Guide (16).

6. **Surface, support and total effective structural numbers.**

7. **Remaining life in terms of ESALs.** Lowest remaining life in fatigue, permanent deformation and serviceability (1993 AASHTO Pavement Design Equation) was calculated and correlated only with corrected measured FWD center deflection for a 5 miles segment of each selected roadway. This remaining life – center deflection relationship was generalized on all segments to provide a simple estimation of remaining life from FWD center deflections only.

8. **Overlay thickness required**. Overlay thickness is estimated using corrected FWD center deflection, deflection values given in Table 3 and two layer analysis.

9. **Coring measured thicknesses of pavement layers.** A limited number of pavement cores were obtained for thickness measurements as a verification sample and to compare thicknesses obtained through coring with those obtained employing FWD and GPR. A core per mile is extracted from some selected roadways.

All response variables were **averaged for each mile** of roadways selected. Variability and reliability parameters were investigated for each response variable. Variability in terms of coefficients of variation is employed for reliability analyses and safety factors computations for all Interstate Highways.

RESULTS AND DISCUSSIONS

GPR at the Project Level

Figures 1 through 3 present GPR pavement thickness analysis along I – 65 north bound driving lane from Reference Post 217 to Reference Post 238. GPR estimated the thickness of the 12" concrete overlay perfectly (Figure 1). However, pavement layers underneath the concrete overlay were not picked by the GPR at all (Figure 1). GPR also estimated the thickness of the 13" HMA overlay almost perfectly (Figure 2). However, the 10" rubblized JRCP pavement layer underneath the HMA overlay was not consistently picked by the GPR (Figure 2). In addition, it appears that the GPR underestimated the thickness of the rubblized layer. GPR also estimated the thickness of the pavement layer representing the 7.5" fiber modified HMA and the pavement layer representing the 10" cracked and seated JRCP (Figure 3). The 8" aggregate base was not picked by the GPR at all (Figures 1 – 3).

FWD at the Network Level

Interstates Structural Conditions

Figure 5 presents profiles of pavement structural characteristics along I – 69. Gaps apparent in these profiles are those stretches that are inside cities. It should be noted that every point represents the average value of 5 measurements per mile. However, it was observed during the analysis process that only 3 measurements per mile would have provided exactly the same information statistically. These profiles were also developed for all other Interstates. The wealth of information that can be obtained from these profiles and used for pavement design, maintenance, rehabilitation and management purposes is apparent. Deflection profiles suggested that all INDOT Interstate Highways were in a very good structural condition based on the criteria given in Table 3. However, this does not necessarily mean that the functional conditions are as good as the structural conditions.

Interstates Comparisons

Figure 6 presents a comparison between all Indiana Interstate Highways selected in the study (both directions). Dotted lines represent the maximum and minimum values and solid lines represent mean values. It can be observed that the mean structural conditions for both directions were almost identical for every Interstate. This suggests that for future testing at the network level, testing only one direction of an Interstate may be representative for this Interstate. Comparison presented in Figure 6 also suggests that the pavement structural conditions of Indiana Interstates were also almost identical. This is expected since these Interstates have similar designs and are exposed to similar traffic classifications and number of traffic repetitions. Standard deviation of performance "S_o" was calculated for every Interstate selected in the study using the procedure reported by Noureldin et.al. (7). Pooled value was found to be 0.497 compared to the value suggested by the 1993 AASHTO Pavement Design Guide of 0.49. Structural conditions (for Interstates) have a calculated reliability level of more than 90% with a safety factor of 4.5.

U.S. Roads and State Routes Structural Conditions

Figure 7 presents profiles of pavement structural characteristics along a 40 mile segment of SR – 32 north bound driving lane. The wealth of information that can be obtained from these profiles and used for pavement design, maintenance, rehabilitation and management purposes is apparent. Profiles of remaining life in terms of ESALs and required overlay thickness are presented in Figure 8. These profiles together with the deflection profile in Figure 7 indicate that some segments of SR – 32 need a structural overlay. The segment between RP – 62 and RP – 70 needs a thick overlay and the segment between RP – 70 and RP – 77 needs a thin overlay (Figure 8). The need for assigning a budget for rehabilitation of these segments and triggering project level evaluations is apparent. These profiles were also developed for all other U.S. Roads and State Routes selected in the study.

U.S. Roads and State Routes Comparisons

Figure 9 presents a comparison between all Indiana U.S. Roads and State Routes selected in the study. It can be observed that the pavement structural conditions are not as identical as when comparing Interstates. This is expected since these roadways do not have similar designs and are not exposed to similar traffic classifications and number of traffic repetitions. This suggests that for future testing at the network level, U.S. Roads and State Routes may need more emphasis than Interstate Highways.

GPR – FWD Thickness Comparisons

Figure 10 presents profiles of GPR – FWD thickness estimation along I – 69 (both north and south bound directions), US – 41 and SR – 32. FWD provided an estimate of the total pavement thickness while the GPR did not. GPR provided an estimate for the thickness of the top surface portion of the combined surface layers while the FWD did not. Top surface portion thickness information is very important for those situations where mill – fill operations are needed.

Thickness profile of combined surface layers estimated using the FWD matched the profile of combined surface layers estimated using the GPR in some segments and was lower than that profile in other segments. This suggests that FWD underestimates the thickness of combined surface layers in some locations. The amount of error, however, is relatively small and can be acceptable for network level evaluation purposes. Profiles obtained from all other Interstate Highways selected in this study were similar to those obtained for I – 69 shown herein.

Coring – GPR Thickness Comparisons

Figure 11 presents profiles of Coring – GPR thickness comparisons along a segment of US – 41 (5” HMA over 10” concrete slab over and 8” aggregate base in some segments and 10” concrete slab over 8” aggregate base in other locations). GPR thickness profile matched the coring thickness profile in the concrete segment perfectly. GPR HMA thickness profile (surface pick 1) matched the coring thickness profile for the HMA layer in the composite segment also perfectly. However, GPR estimate for the combined surface was lower than coring by 1 to 5 inches but followed a similar pattern to coring profile. It might be important to indicate herein that during coring, rebar was detected exactly at the locations that were picked by the GPR as an interface. Authors believe that the first GPR pick is consistently accurate. However, limited coring may still be needed to adjust the measurements of second and or third picks. The second and third picks (when detected) appear to be accurate in some situations and need adjustments in other situations.

FINDINGS AND CONCLUSIONS

This paper presents Indiana experience in pavement evaluation with FWD and GPR at the network level. A network level FWD and GPR testing program was implemented as a part of a study to overcome traditional obstacles for the use of FWD and GPR in pavement evaluation at that level namely; expenses involved in data collection, limited resources and lack of simplified analysis procedures. This testing program included Interstate Highways I – 64, I – 65, I – 69, I – 70 and I – 74 and a number of U.S. Roads and State Routes. Main findings and conclusions can be summarized as follows:

- Network level testing employing FWD and GPR is a worthwhile, technically sound program that will provide a baseline of structural capacities of in – service pavements in Indiana. Periodical generation of necessary data will be useful for determining how best to quantify the loss in structural capacity and estimate annual construction budget.
- The wealth of information that is obtained through network level testing can be used for pavement design, maintenance, rehabilitation and management purposes.
- Both FWD and GPR data is recommended to be used as part of INDOT pavement management system.
- FWD data on 2200 lane miles of the INDOT network is recommended annually for network level pavement evaluation. Only three FWD tests per mile in the driving lane of one direction are recommended. The information collected will allow the equivalent of 100% coverage of the whole network in 5 years.
- U.S. Roads and State Routes may need more emphasis in network level testing than Interstate Highways.
- GPR data is recommended to be collected once every 5 years (if needed) after the successful network thickness inventory conducted in this study. GPR data collection is also recommended at project level and for special projects.
- A pavement thickness and structural capacity inventory of INDOT Interstate Highways was developed. INDOT Interstate Highway pavements are currently in a very good structural condition.
- GPR estimates concrete thickness of concrete pavements, HMA thickness of flexible pavement and HMA thickness of composite pavements almost perfectly. GPR thickness estimation of pavement layers underneath these layers is not as accurate and needs adjustment through very limited coring. GPR (used in this study) did not provide any estimate of unbound pavement layers or total pavement thickness.
- FWD estimates total pavement thickness when using the simplified method presented in this paper. FWD also estimates combined surface thickness. This estimate matched the GPR estimate in some situation or was slightly lower.
- GPR is not expected to completely eliminate the need for coring. GPR can be used to establish the coring requirements to help interpret the GPR data fill the gaps in thickness estimation and verify thickness results.
- Pooled standard deviation of performance for INDOT interstate highways is 0.497, reliability level is 90% and safety factor is in the range of 3.8 to 5.2.

REFERENCES

1. Haas, R., Hudson, W.R., and J.P. Zaniewski, “Modern Pavement Management”, Krieger Publishing Co., Malabar, Florida, 1994.
2. Nondestructive Testing of Pavements and Backcalculation of Moduli, STP 1198, American Society for Testing and Materials, ASTM, H. L. Von Quintus, A. J. Bush, and G. Y. Baladi, Editors, December 1994.
3. Von Quintus, H. L., and B. Killingsworth, “Backcalculation of Layer Moduli of SHRP – LTPP General Pavement Study (GPS)”, Publication No. FHWA – RD – 97 – 086, Federal Highway Administration, July 1997.
4. Noureldin, A. S., Sharaf, E., Arafah, A., and Al-Sugair, F., “Use of Falling Weight Deflectometer to Determine Pavement Deflection Characteristics”, Proceedings, 12th IRF World Congress, Madrid, Spain, May 1993.
5. Noureldin, A. S., “New Scenario for Backcalculation of Layer Moduli of Flexible Pavements”, TRR 1384, Washington, D.C., 1993.
6. Noureldin, A. S., “Influence of Stress Levels and Seasonal Variations on In-Situ Pavement Layer Properties”, TRR 1448, Washington, D.C., 1994.
7. Noureldin, A. S., Sharaf, E., Arafa, A., and Al-Sugair, “Rational Selection of Factors of Safety in Reliability Based Design of Flexible Pavements”, TRR 1540, Washington, D.C., 1996.
8. Noureldin, A. S., “Seasonal Deflections and In Situ Moduli Patterns of Polymer Modified Versus Unmodified Asphalt Pavements”, Proceedings, Mechanical Tests for Bituminous Materials, Lyon, France, March 1997 RILEM, PP 583-590.
9. SHRP Product Catalog, Strategic Highway Research Program, National Research Council, Washington, D.C., 1992.
10. Wenzlick, J., Scullion, T. and K. R. Maser, “High accuracy Pavement thickness Measurement Using Ground Penetrating Radar”, Final Report, RDT 99 – 003, R I96 – 11, PTP, Missouri Department of Transportation, February 1999.
11. NCHRP Synthesis No. 255, “Ground Penetrating Radar for Evaluating Surface Conditions for Transportation Facilities”, A Synthesis for Highway Practice, TRB Synthesis Studies, National Research Council, Washington, D.C.
12. J. J. Daniels, “Fundamentals of Ground Penetrating Radar”, Soft Earth Associates Inc., Westerville, Ohio, 1990.
13. J. B. Hasted, “Aqueous Dielectrics”, London, Chapman and Hall, 1973
14. Ulriksen, C., F. Peter “Application of Impulse Radar in Civil Engineering”, Doctoral Thesis, Department of Engineering Geology, Lund University of Technology, Lund Sweden, reprinted and distributed by Geophysical Survey Systems Inc., North Salem, New Hampshire, 1982.
15. D. A. Harris, “A GPR Based Underground Workings Monitoring Program for Surface Mines”, M.S. Thesis, Department of Mining Engineering, Montana Tech of the University of Montana, Butte, MT, 1998.
16. AASHTO, “AASHTO Guide for Design of Pavement Structures”, American Association of state Highway and Transportation Officials, 1993.

DISCLAIMER

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Indiana Department of Transportation or the Federal Highway Administration. This paper does not constitute a standard, specification or regulation.

ACKNOWLEDGEMENTS

This study was supported by the Indiana Department of Transportation, INDOT, under the Joint Transportation Research Projects, JTRP, Program. Authors would like to acknowledge study advisory committee members; Mr. Lee Gallivan, from FHWA, Mr. William Flora, Mr. Kumar Dave and Mr. Nayyar Zia from INDOT, Prof. Vince Drnevich from Purdue and Mr. John Weaver from Deighton Consulting Group, Inc. and FWD testing program coordinators and testing crew; Mr. Larry Bateman, Mr. David Hinshaw, Mr. Mike Murdock, Mr. Danny Heath and Mr. Jim Wooten.

Table 1: Relative Dielectric Constant (11)

Material	Mean	Range
Portland Cement Concrete	9	6 – 12
Asphalt Concrete and Dry Sand	5	3 – 7
Rock	9	6 - 12
Dry Aggregate Base/ Subbase	7	5 – 9
Wet Aggregate Base/Subbase	15	10 – 20*
Subgrade	15	5 – 25*
Air	1	
Water	80	

Note: Values larger than 15 represent full saturation and values larger than 10 represent partial saturation.

Table 2: GPR Minimum Detectable Pavement layer Thickness

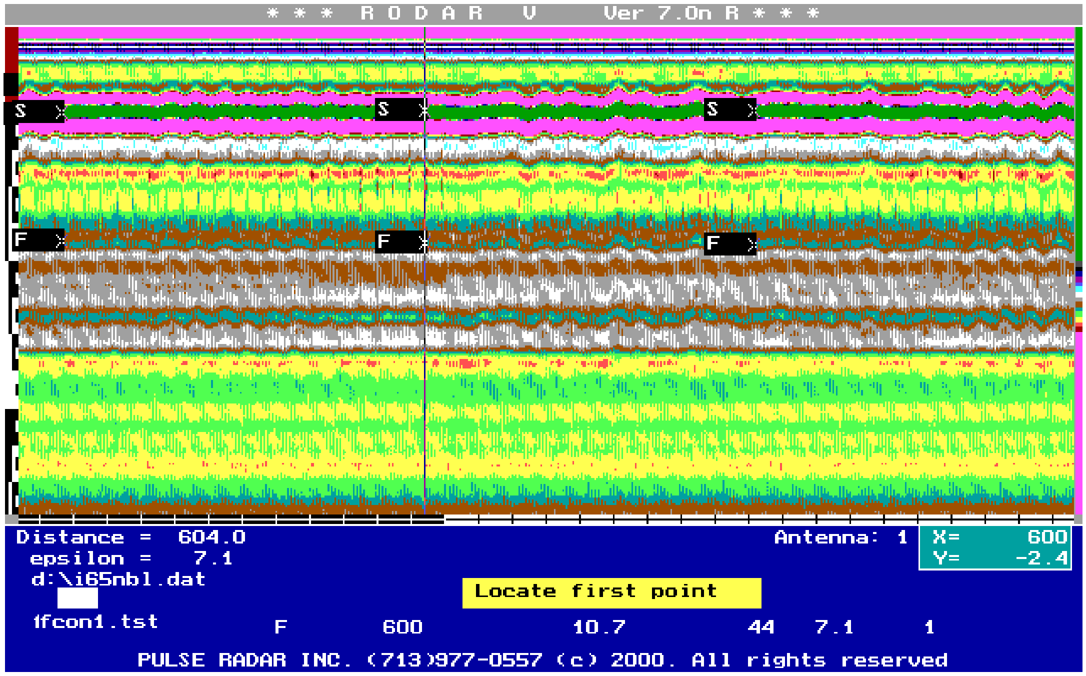
Antenna Frequency	500 MHz		1 GHz	
Surface Type	Asphalt	Concrete	Asphalt	Concrete
Dielectric Constant	4.0	7.1	4.0	7.1
Minimum Thickness, inches	3.00	2.25	1.5	1.125

Table 3: Pavement Structural Condition as Defined by Center Deflection in mils for a 9000 Pounds Load at 68 F

Condition	Interstates	Heavy Traffic	Medium Traffic	Light Traffic
Excellent	< 4	< 5	< 6	< 8
Very Good	4 – 6	5 – 7	6 – 8	8 – 10
Good	6 – 8	7 – 9	8 – 10	10 – 12
Fair	8 – 10	9 – 11	10 – 12	12 – 14
Poor	> 10	> 11	> 12	> 14
ESALs, Millions	> 30	10 – 30	3 – 10	< 3

Table 4: Temperature Correction Factors for FWD Center Deflection

Mean Pavement Temperature, F	41	50	59	68	77	86	95	104	113	122
Temperature Correction Factor	0.74	0.81	0.90	1.00	1.11	1.22	1.34	1.46	1.59	1.72



I - 65 North Bound Driving Lane

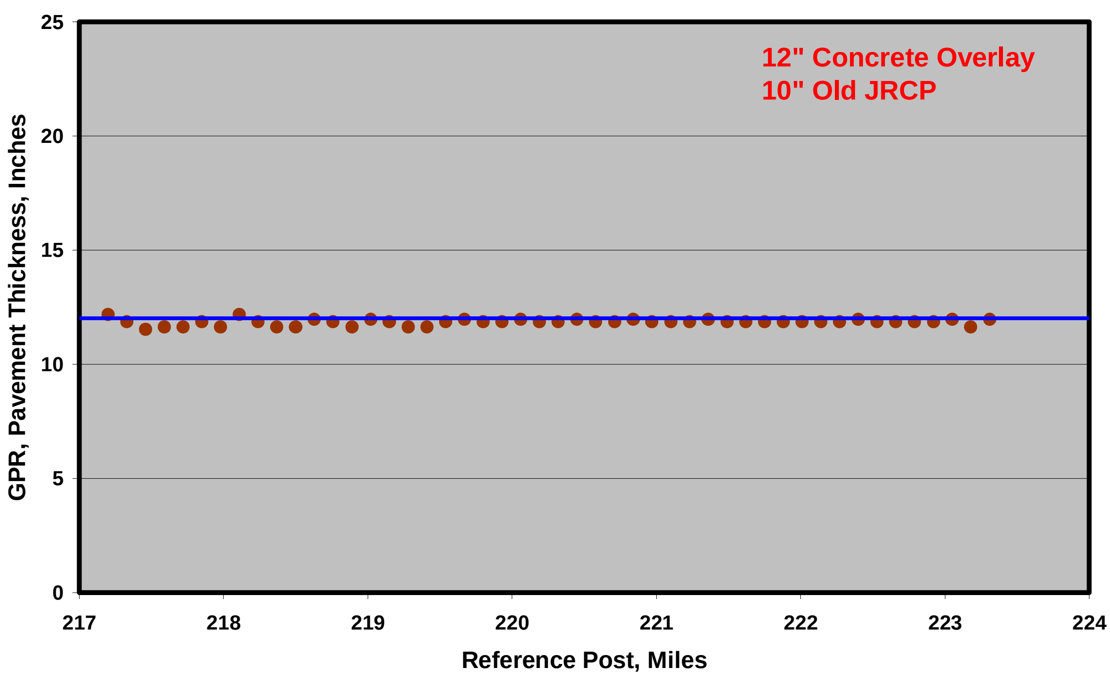
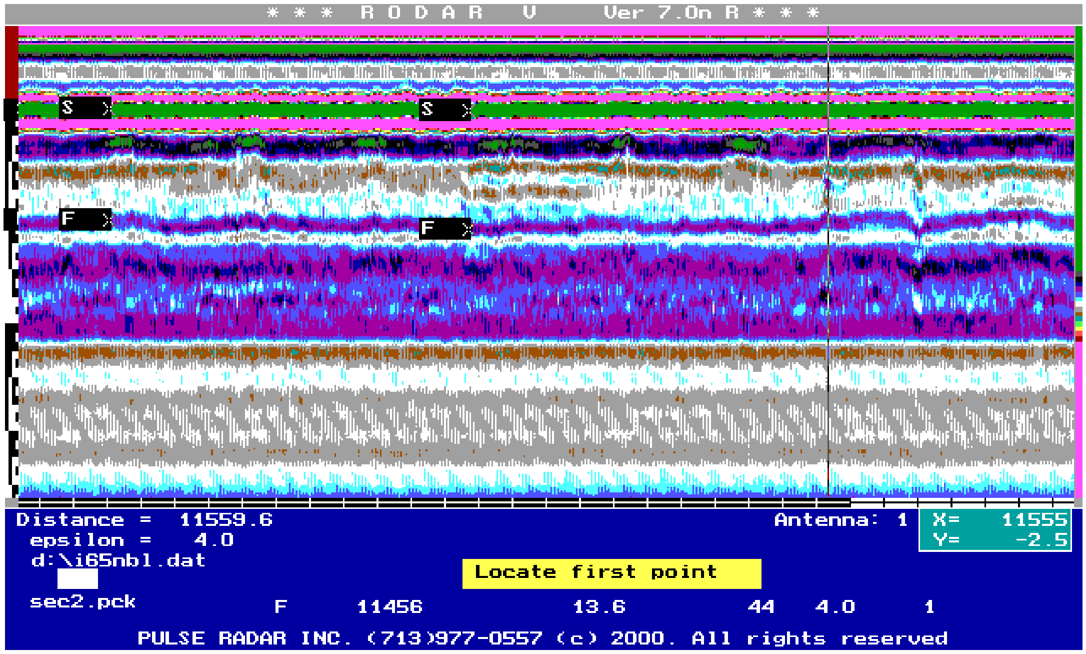


Figure 1: GPR Scan from a 12" Concrete Pavement over a 10" Old JRCP over an 8" Aggregate Base on I – 65



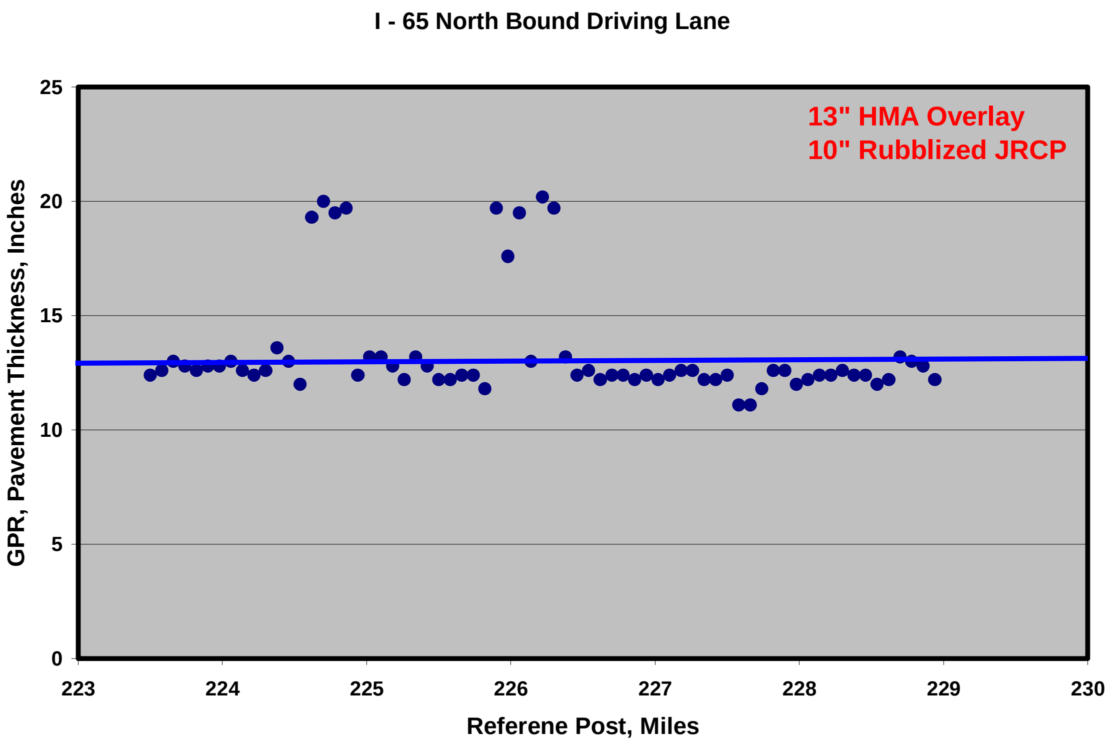
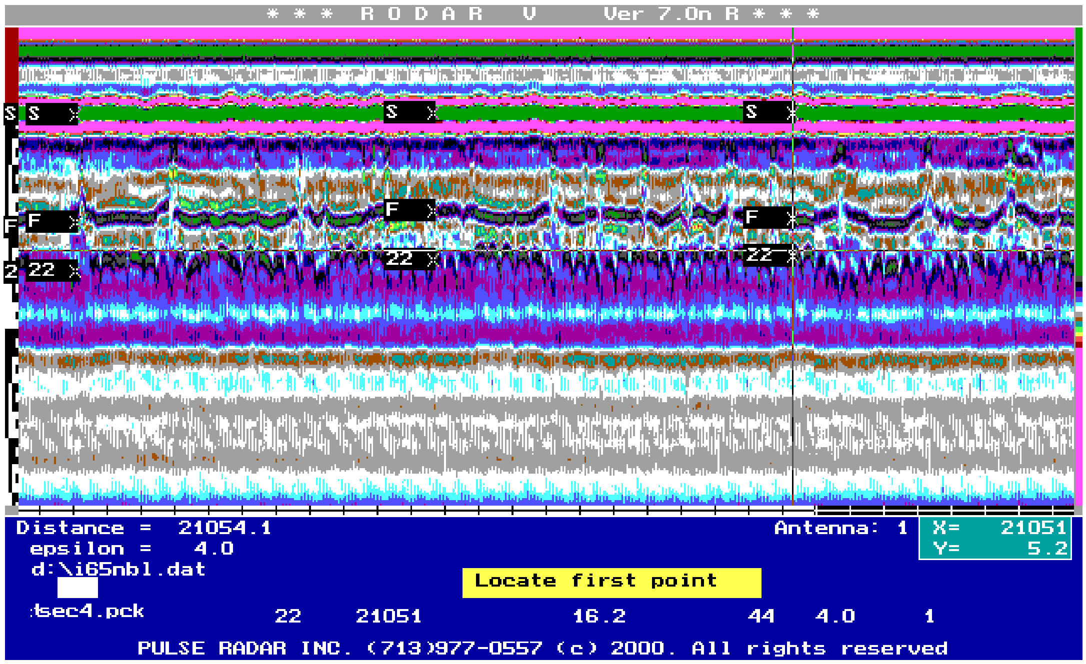


Figure 2: GPR Scan from a 13" HMA Pavement over a 10" Rubblized JRCP over an 8" Aggregate Base on I – 65



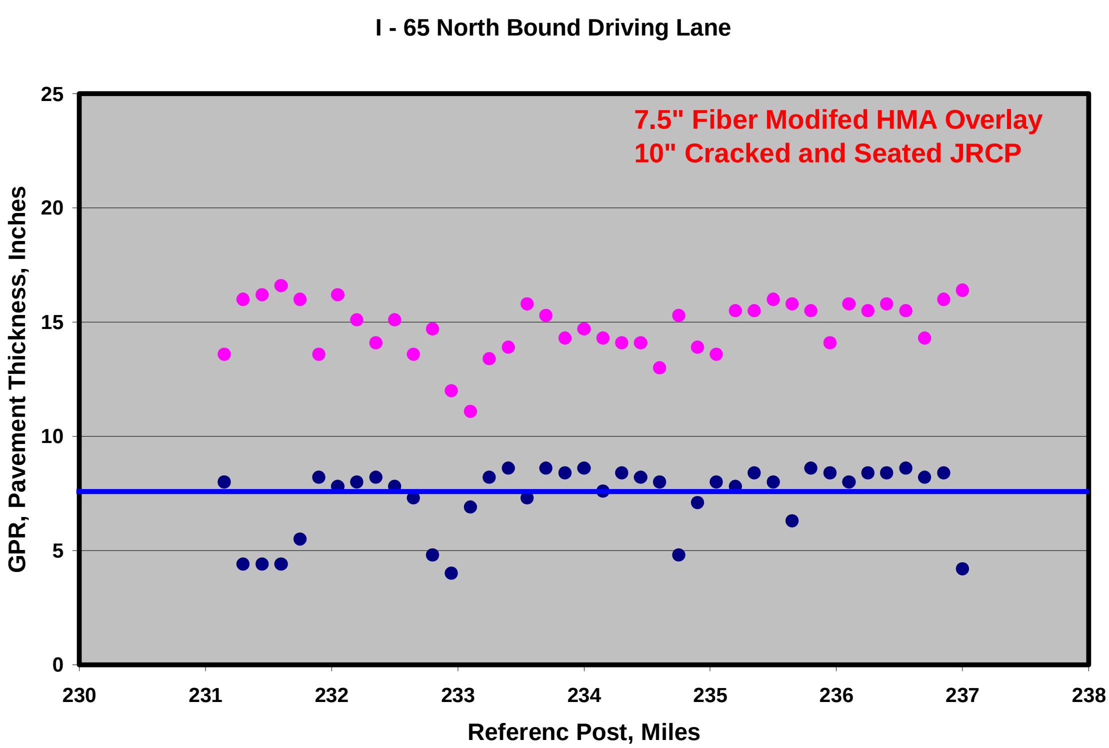


Figure 3: GPR Scan from a 7.5" Fiber Modified HMA Pavement over a 10" Cracked and Seated JRCP over an 8" Aggregate Base on I – 65

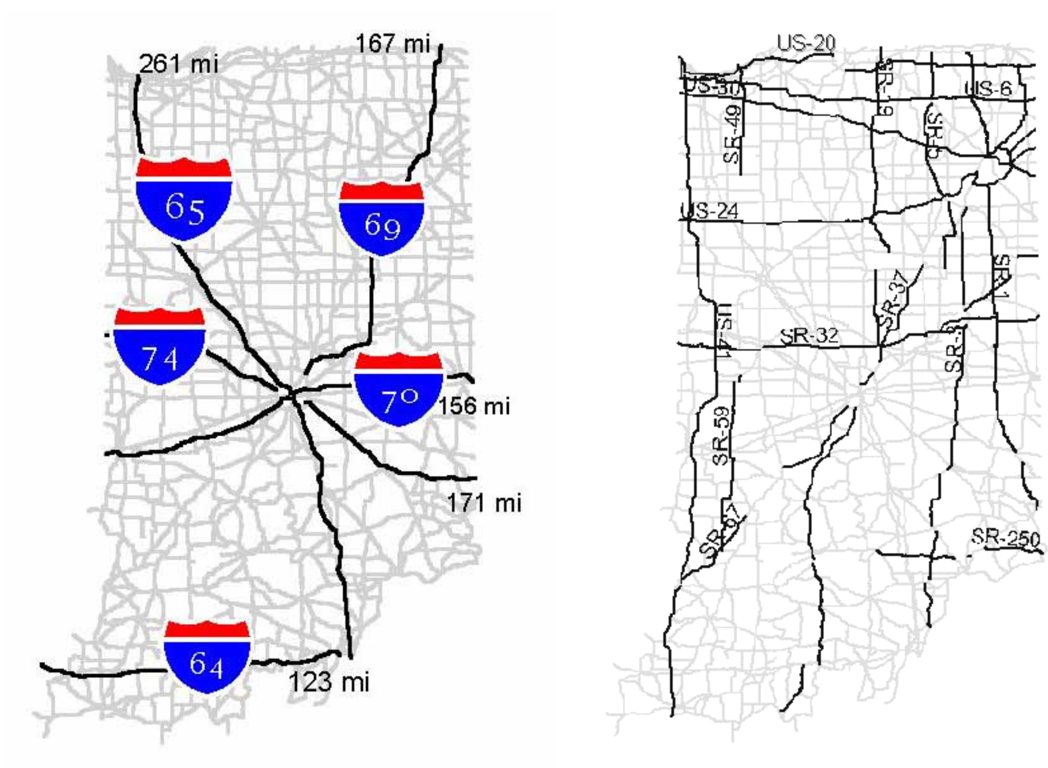


Figure 4: Interstate Highways, U.S. Roads and State Routes Tested During the Study

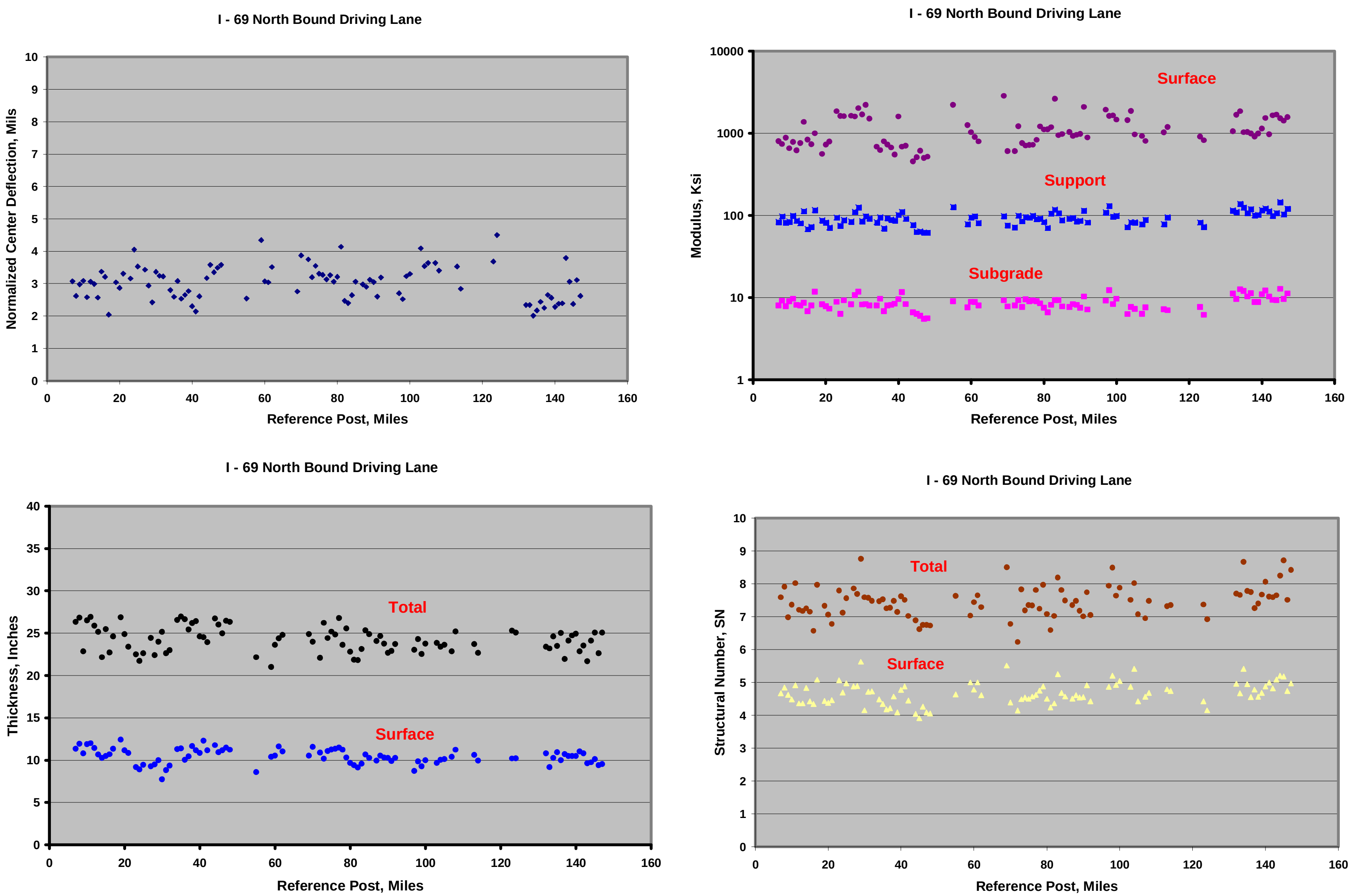


Figure 5: Profiles of Pavement Structural Characteristics along Interstate I – 69

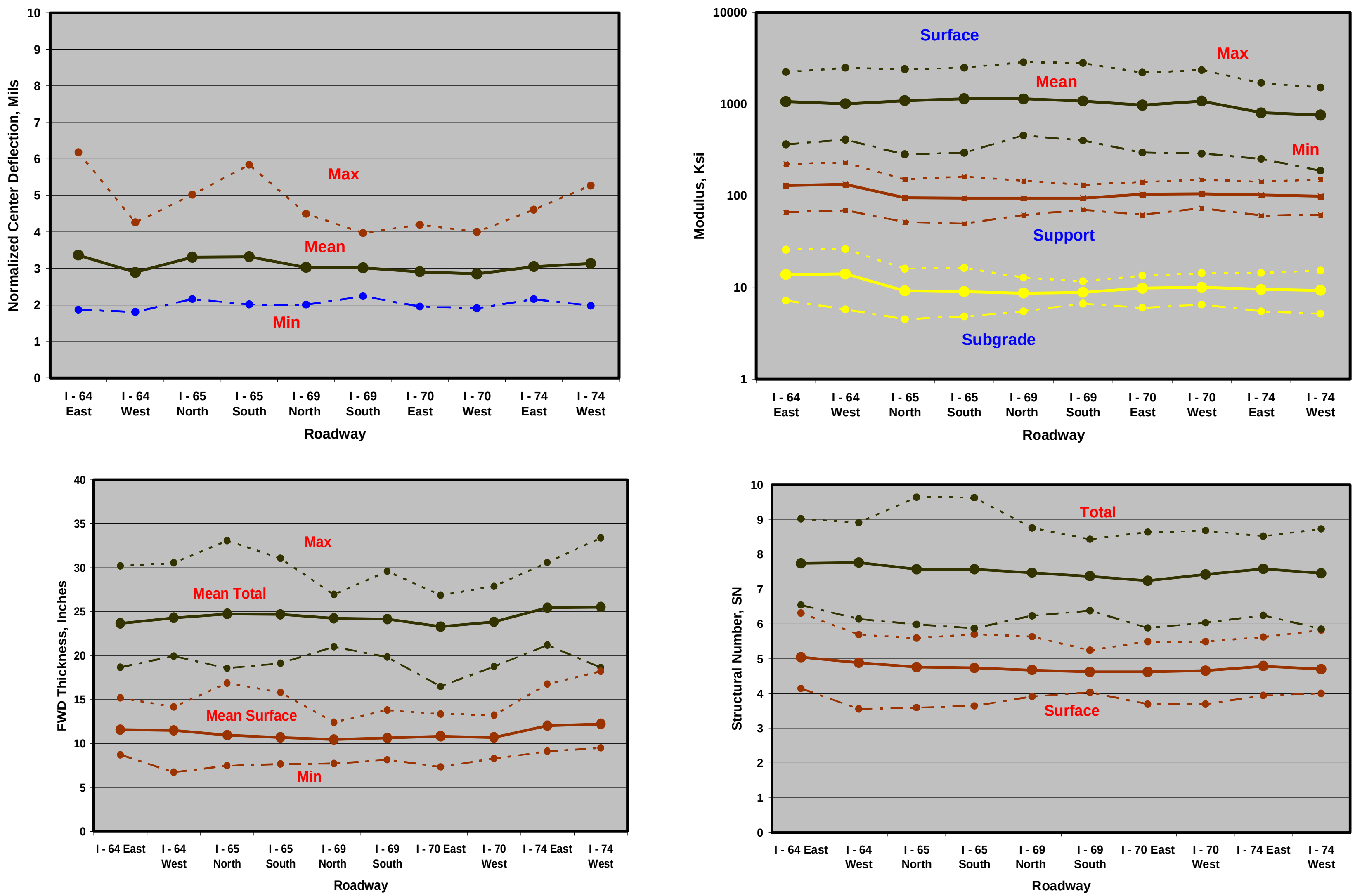


Figure 6: Interstate Comparisons

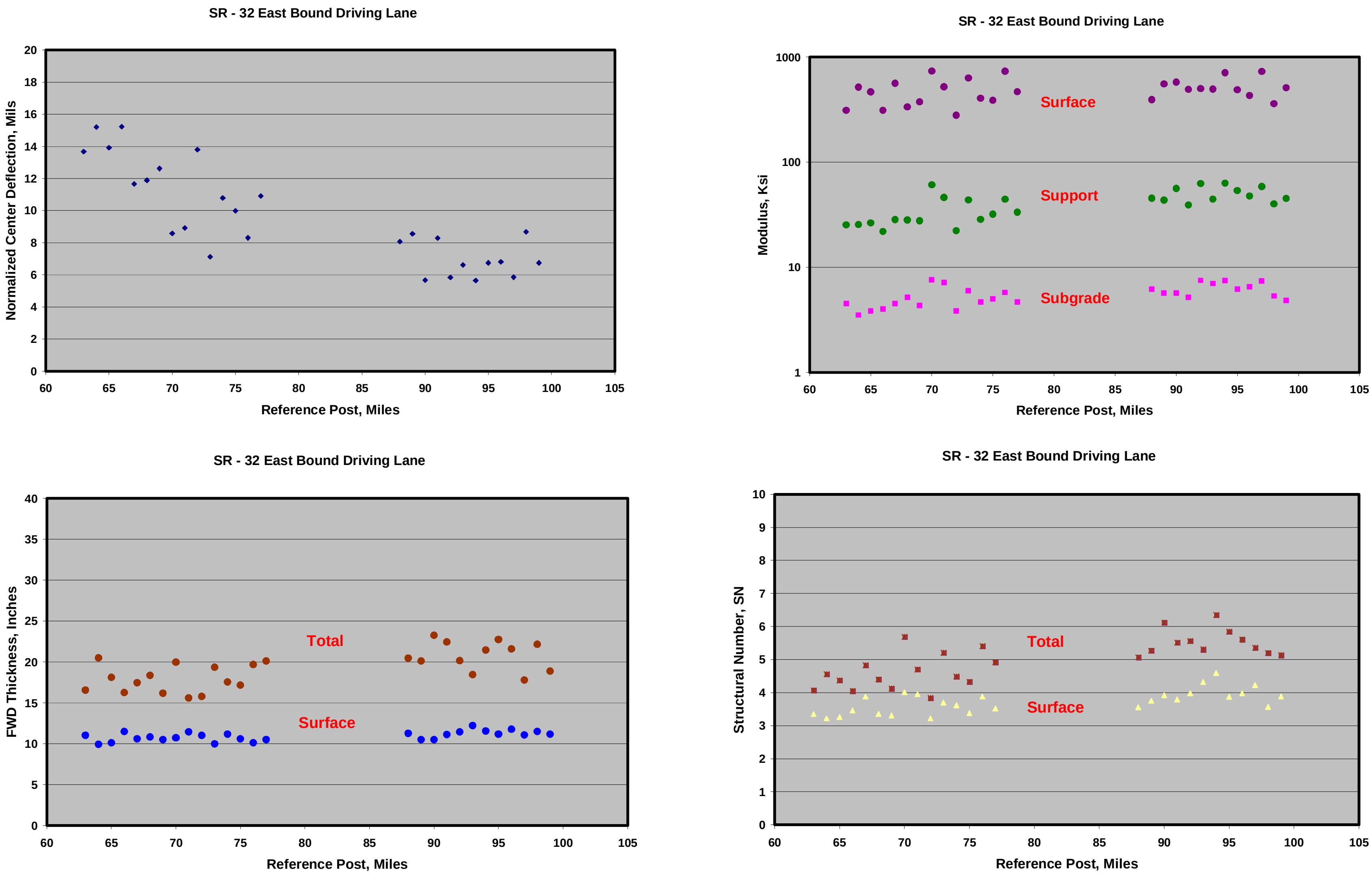
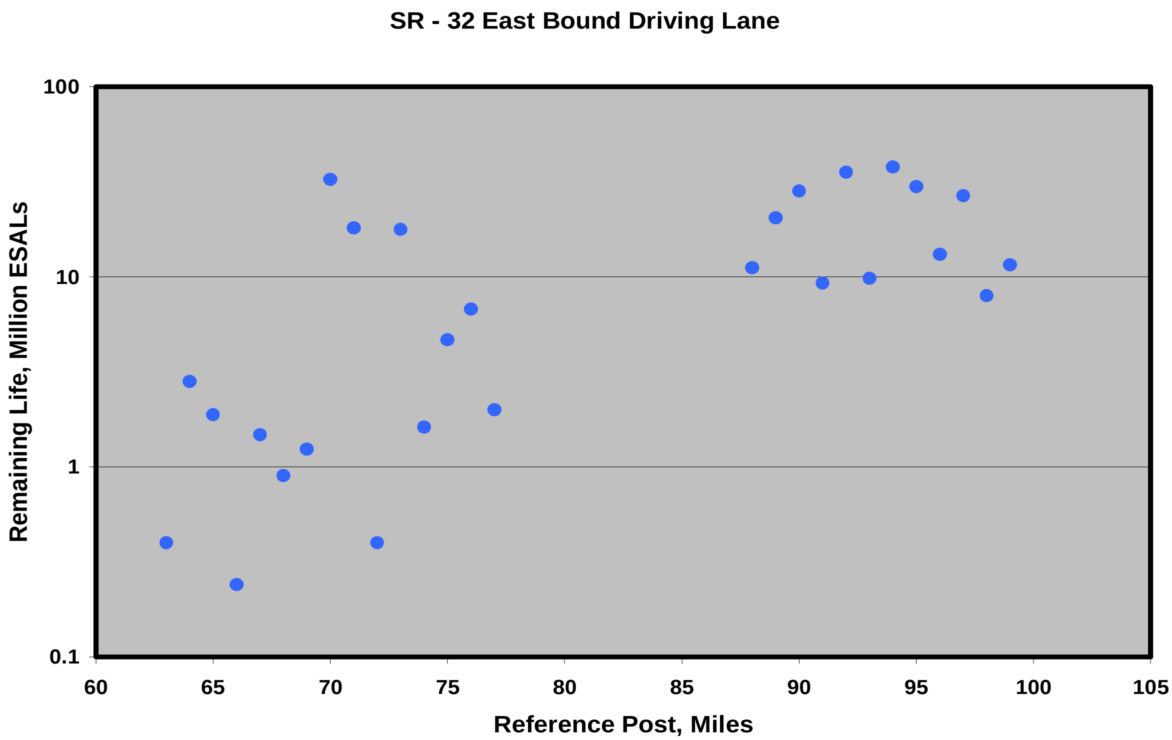


Figure 7: Profiles of Pavement Structural Characteristics along SR – 32



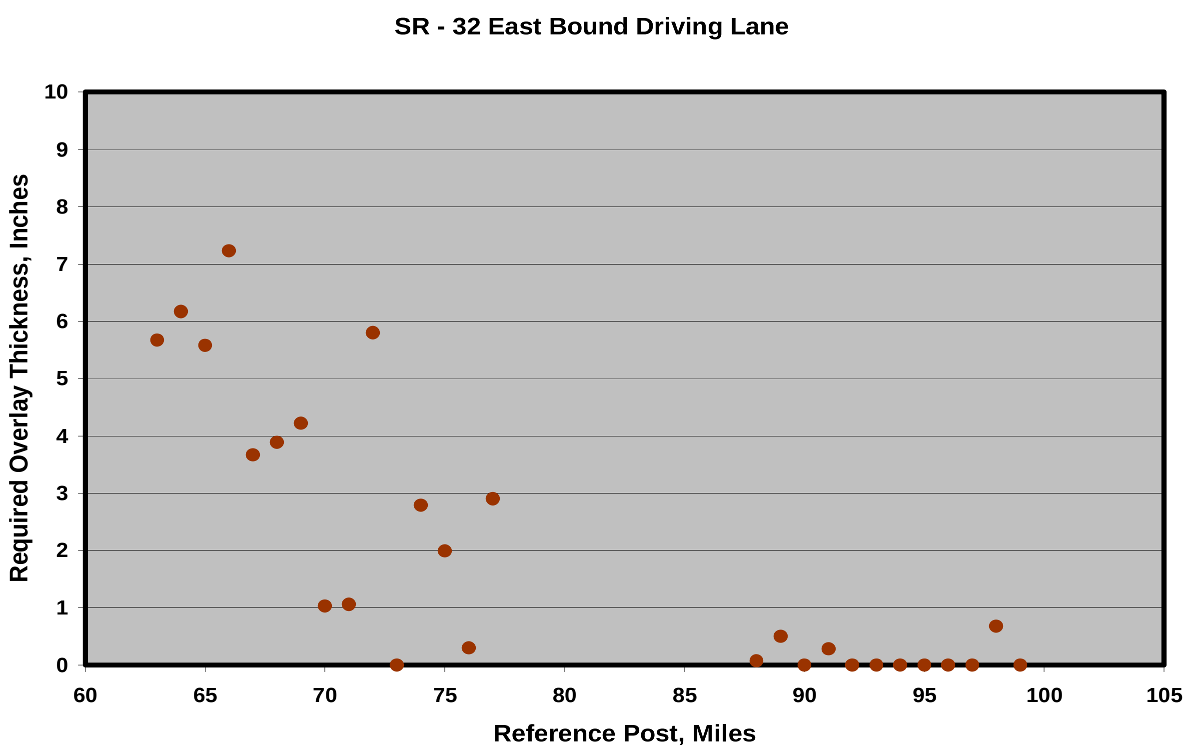
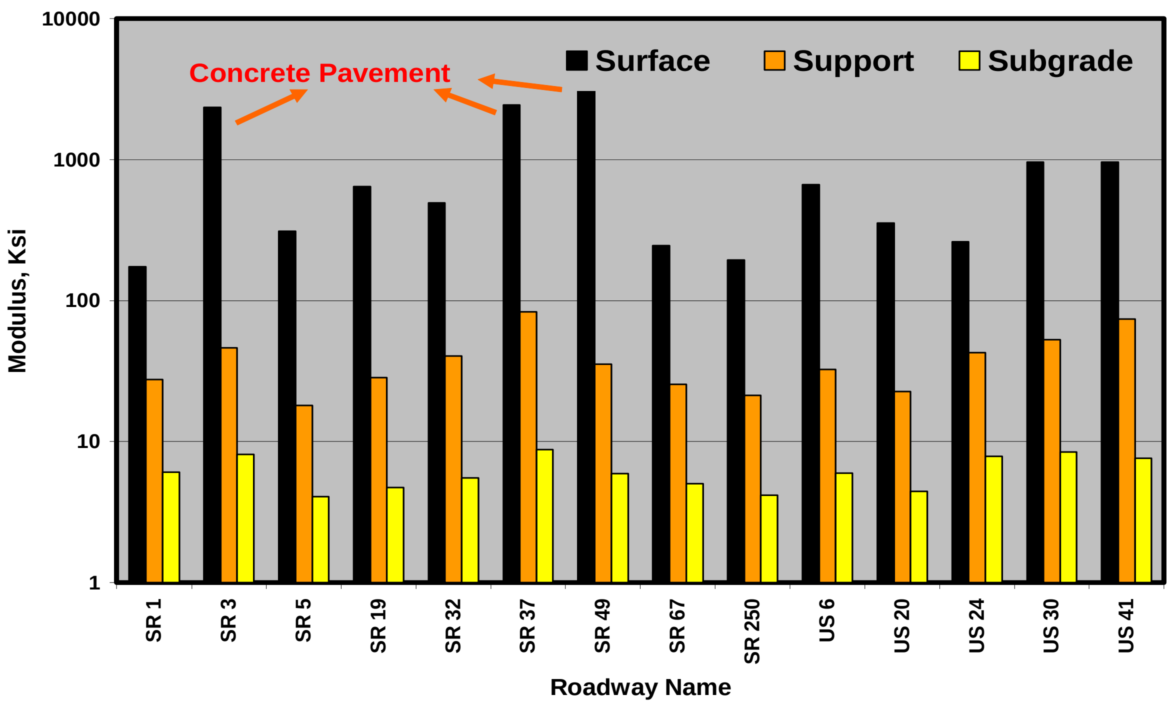


Figure 8: Profiles of Remaining Life and Required Overlay Thickness along SR – 32



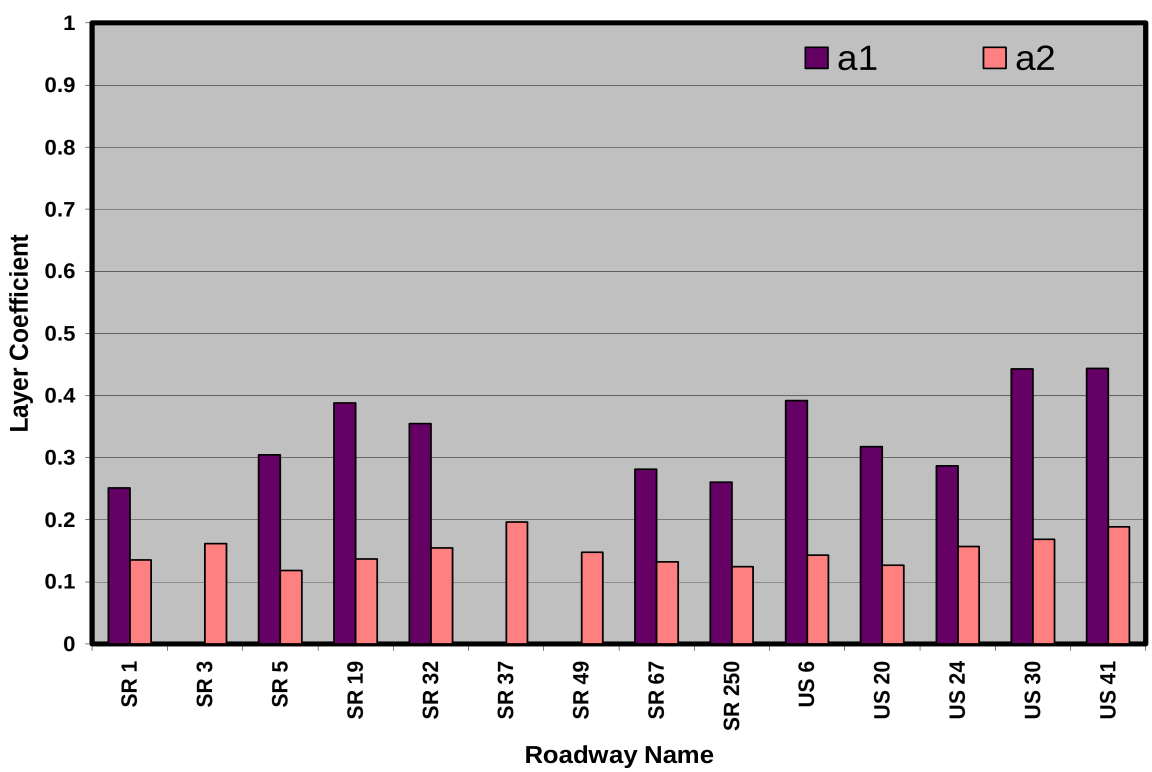


Figure 9: U.S. Roads and State Routes Comparisons

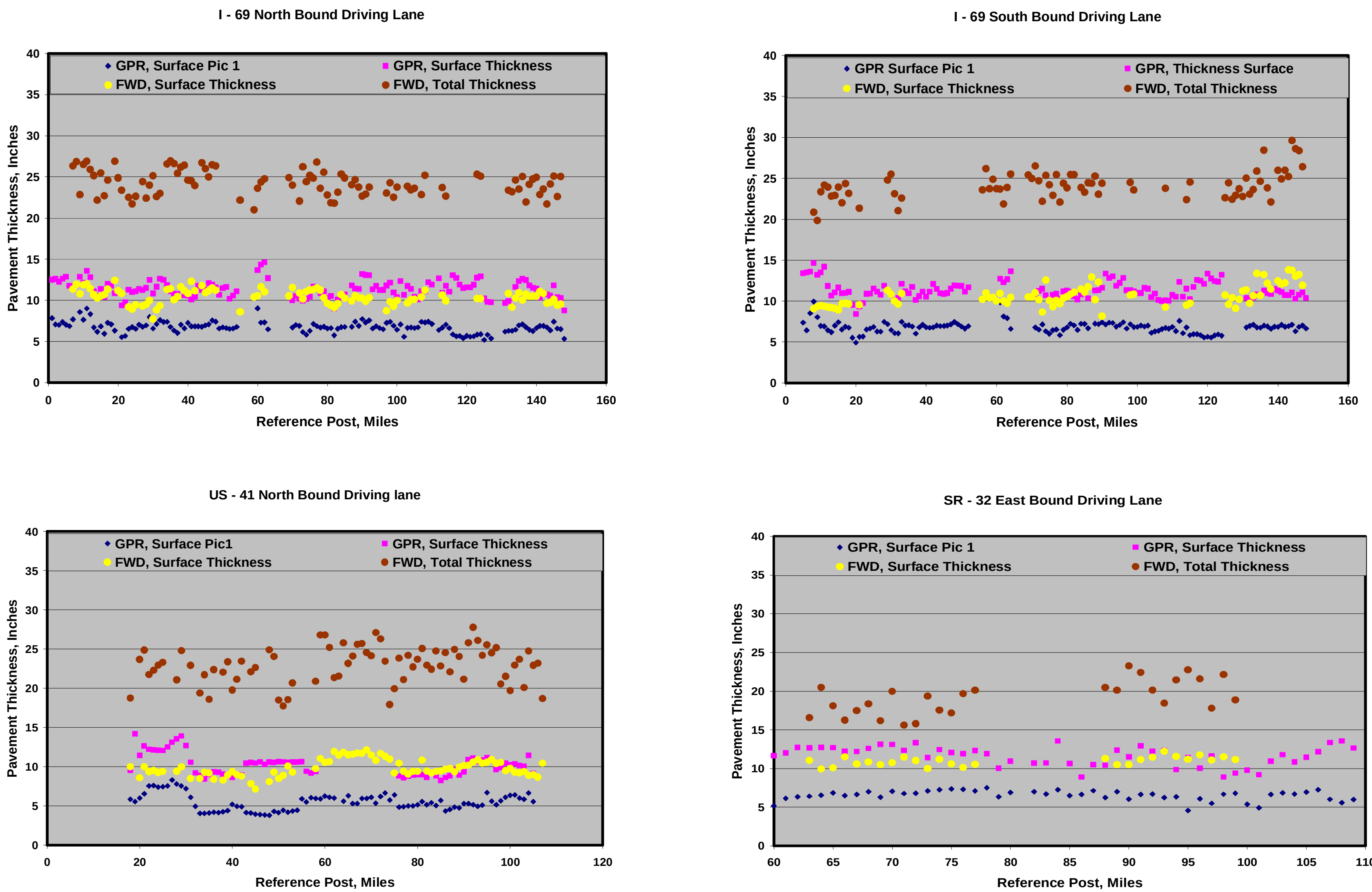


Figure 10: GPR – FWD Thickness Comparisons

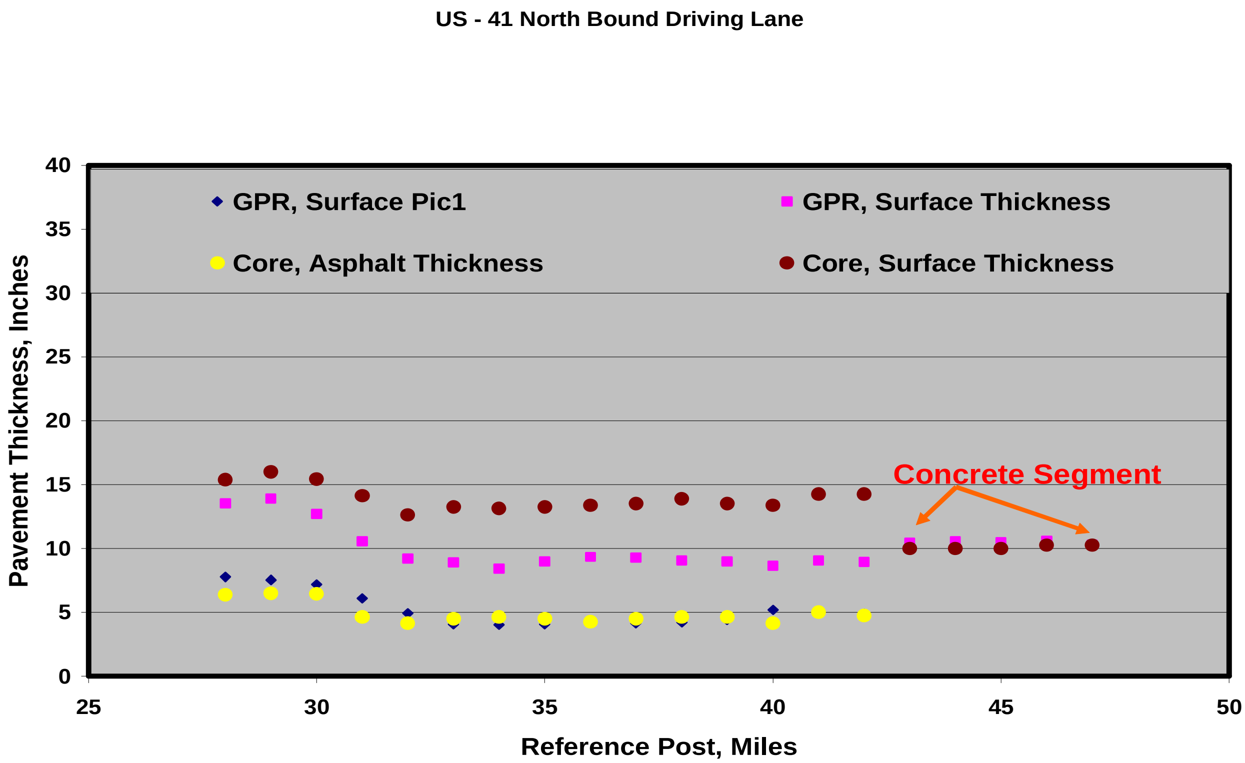


Figure 11: Coring – GPR Thickness Comparisons